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ABSTRACT

This selective annotated bibliography covers various sources of information on the radiocarbon dating method, including journal articles, conference proceedings, and reports, reflecting the most important and useful sources of the last 25 years. The bibliography is divided into five parts--general background on radiocarbon, radiocarbon dating, laboratory methods, limitations and sources of errors, and calibration of the radiocarbon chronology. Extensive introductory materials include characteristics of the literature, discussion of radiocarbon dating, the author's observations based on a personal tour of the Radiocarbon Laboratory at the University of Texas, and a listing of radiocarbon laboratories around the world. The bibliography was compiled from the sources available at the University of Texas as of April 1977. (Author/BBM)

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RADIOCARBON DATING

AN ANNOTATED BIBLIOGRAPHY

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IR005402

L.S. 382L.4
E.B. Jackson
April 25, 1977

"Bubbles from the Swamp"

I think that I shall never see
A sample of a plain old tree.
A tree that's not been carved or painted,
Calcified, burned, or otherwise tainted.
But bones and shells and peat I get;
Preparing them, all day I sweat.
Won't someone please take pity on me,
And send in just one plain old tree.

Poem read by T.A. Rafter at the
Sixth International Conference:
Radiocarbon and Tritium Dating,
1965.

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PREFACE

My personal interest in radiocarbon dating began sometime in 1974, when my husband, Gary (who was not yet my husband at that point) was involved in archaeological lab and field work. I remember him telling me with his usual enthusiasm that some of the artifacts he had been working with were going to be sent off for carbon-14 dating. I was curious and he explained the process to me. Now I am glad to have had the opportunity to explore the subject in more depth and I hope this bibliography will someday prove helpful to him.

In addition to expressing general appreciation to the librarians in the several libraries I used in compiling my bibliography, I would also like to extend special thanks to the following people who were particularly helpful. First, to Martin Smith of the Geology Library, who was extremely helpful and patient on several occasions. Next, to Dr. E. Mott Davis, Director of the U.T Radiocarbon Laboratory, who provided access to some materials not available through the libraries and who arranged for my visit to the Radiocarbon Lab. And, finally, my warmest thanks go to Mrs. Alejandra Varela and Mr. Sam Valastro of the Radiocarbon Lab, who were gracious and generous in giving me an interesting tour of the lab and an opportunity to observe firsthand many of the processes involved in the radiocarbon dating process.

INTRODUCTION

The primary purpose of my research has been to compile an annotated bibliography of the most important and useful articles, reports, papers and other sources of information on the radiocarbon dating method. In the section immediately following this introduction, I have outlined my basic strategy and the reasons underlying my choice of that particular strategy. Next is a discussion of the characteristics of the literature on radiocarbon, based on the results of my search. The next section of the paper is a brief introduction to radiocarbon dating, to acquaint the reader with the fundamental principles, laboratory methods, and problems involved in radiocarbon dating. The bibliography, which has been divided into five parts, follows the section on radiocarbon dating.

STRATEGY

In developing a strategy for compiling this bibliography, there were two major factors which greatly influenced the scope of my intended research. The first had to do with the time period involved. Due to the fact that the radiocarbon dating method was developed in the late 1940's, the time span covered by my research had a natural limit of approximately thirty years.

The second factor which influenced the scope of my search was the extremely cross-disciplinary nature of the applications of radiocarbon dating. While the method of dating with carbon-14 was developed by a chemist and is usually performed by chemists, geochemists and geophysicists, the results are used by geologists, archaeologists, paleobotanists, soil scientists and climatologists, to name only the most prominent users. The field of archaeology posed a particular problem in terms of my search. Whereas the other disciplines mentioned are all covered by one or another of the scientific indexing/abstracting services, articles on archaeology tend to appear in journals classified in the humanities and social sciences as well as in scientific journals. I therefore found it necessary to extend my search somewhat beyond the realm of the pure and applied sciences to ensure retrieval of all pertinent sources.

My strategy itself consisted of several distinct processes. I first located the major monographs on the subject by consulting the card catalog at the Main Library. Several of these, particularly the conference proceedings I found, had excellent bibliographies, which when exploded provided a good source of retrospective articles, as well as a guide to the

journals which would be likely to carry later articles on the subject.

The second step in my strategy was checking the indexing and abstracting services for more current articles and reports. Using the list of journals I had compiled, I checked all indexing sources necessary to ensure that the important journals had been covered. On the following page is a list of indexing/abstracting sources I checked, including dates of coverage as well as subject headings used in each.

Because my intention was to obtain supplementary current articles from these sources, I did not think it necessary to search further back than 1972 in most cases. The exceptions were sources in which it was either convenient or necessary due to the structure of the indexes, to cover earlier years.

My search of these sources provided me with a wealth of references, as well as a much clearer idea of the scope and types of articles published on radiocarbon dating. At this point, I decided to place two arbitrary limits on my inclusions: first, of the older sources, only the very most valuable or landmark publications would be included; second, all archaeological reports of radiocarbon dating applied to particular sites, which numbered in the hundreds, would be excluded completely.

Before starting the selection and evaluation process, I took one final step to ensure retrieval of all relevant sources. I did a citation search using both Science Citation Index and Social Science Citation Index.

Using W.F. Libby's book Radiocarbon Dating (16), the seminal work in the field, as a starting point, I checked both citation indexes for the years 1972-1977. In this way, I was able to locate all authors who had cited Libby's book over that period of time. This method yielded some additional references, as well as many which I had found earlier and some

which were irrelevant.

Having completed the final step in my retrieval process, I next spent several hours in the PMA, Geology, Engineering, Main and Classics Libraries, plus a brief visit to the Chemistry Library, scanning, reading, and in some cases abstracting articles to include in the bibliography.

The above articles comprised the major part of my literature search, which provided almost all of the material for the bibliography. To complement the literature search, I also contacted Dr. E. Mott Davis, Head of the Radiocarbon Laboratory at U.T. and was permitted to visit the lab. A description based on my visit appears in a later section of this paper.

INDEXING/ABSTRACTING SERVICES SEARCHED

SERVICE	YEARS	SUBJECT HEADING(S)
Applied Science & Technology Index	1968-1977	Carbon - Isotopes
Bibliography and Index of Geology	1969-1976	Carbon - Isotopes
Chemical Abstracts	1972-1977	Carbon - Isotope of Mass 14
Engineering Index	1972-1977	Carbon - Isotopes
Humanities Index	1974-1976	Radiocarbon Dating
INIS Atomindex	1975-1977	Carbon-14; Archaeological Specimens Isotope Dating
Nuclear Science Abstracts	1969-1975	Archaeology; Carbon-
Physics Abstracts	1972-1977	Radioactive Dating
Social Sciences and Humanities Index	1965-1974	Radiocarbon Dating; Archaeology, Stratigraphic
Social Sciences Index	1974-1976	Radiocarbon Dating

CHARACTERISTICS OF THE LITERATURE ON RADIOCARBON DATING

This brief discussion of the characteristics of the literature on radiocarbon dating focuses on two aspects of the literature: 1) Where and in what form is information on radiocarbon dating published? and 2) What persons and/or institutions have been most active in research and in publishing the results of their research in the field?

To answer the first question based on my literature search, I compiled the following table, using 188 references to articles, papers, reports, etc., which I had located.

LOCATION OF ARTICLE, ETC:	
CONFERENCE PRODEEDINGS	30
PARTS OF BOOKS	27
JOURNALS ..... TOTAL	131
American Antiquity	13
Nature	13
Journal of Geophysical Research	10
Science	10
Antiquity	7
Review of Scientific Instruments	7
Philosophical Trans. Royal Soc.	6
International Journal of Applied Radiation and Isotopes	5
Archaeometry	4
Journal of Geology	4
Analytical Chemistry	2
American Journal of Archaeology	2
Bulletin, Geological Soc. America	2
Current Anthropology	2
Journal of African History	2
New Zealand Journal of Science	2
Research	2
Zeitschrift Naturforsch	2
Journals containing only one article...	29
Physical Review (omitted above)	5
Nucleonics " "	2

From these admittedly limited data, it is nonetheless possible to make some general observations. First, the cross-disciplinary nature of

radiocarbon dating is underscored by the diversity of journals carrying articles, the large number of articles with only one article, and the lack of an apparent single leading journal. (Note: the journal Radiocarbon, which is used for publishing lists of dates almost exclusively, and which rarely carries articles, was excluded from consideration.)

The importance of conference proceedings is also apparent. There have been eight international conferences on radiocarbon dating, which have been a major vehicle for the presentation and discussion of new techniques and procedures.

To answer the second question, it was necessary to have read and studied the literature somewhat more thoroughly than for the previous question. The following discussion of some important people in the field and the radiocarbon labs where their research has been done is based on a rather thorough study of the literature.

A notable achievement of the University of Texas Radiocarbon Laboratory was the development of the liquid scintillation counter for radiocarbon dating. Dr. E. Mott Davis is the head of this lab. The University of Arizona is known primarily for its research in dendrochronology or tree-ring chronology and radiocarbon correlation, done under the direction of former director, Dr. Paul E. Damon. The University of Chicago Institute of Nuclear Studies is the site where Dr. Willard F. Libby did his pioneering work in the 1940's; Dr. Libby is now with the Institute of Geophysics at the University of California (Los Angeles).

The Mt. Soledad Radiocarbon Laboratory of the University of California (San Diego) at La Jolla, has been active in radiocarbon measurements of tree-ring materials. The head of the La Jolla lab is Dr. Hans E. Suess, who is prominent for his development of a calibration curve for radiocarbon-dendrochronology correlation.

The lab at the University of Pennsylvania has also been involved in the radiocarbon measurement of the tree-ring chronology. The director at Pennsylvania, Dr. Elizabeth K. Ralph, is the joint author of the book, Dating Techniques for the Archaeologist (19), as well as two excellent articles (20, 59).

Dr. Minze Stuiver of the Quaternary Isotope Laboratory at the University of Washington, Dr. Ingrid U. Olsson of the radiocarbon lab at the University of Uppsala, Sweden and Professor Hl. DeVries former director of the lab at Groningen, The Netherlands have all also been actively involved in the research in this field.

RADIOCARBON DATING

Radiocarbon dating is a method of estimating the age of carbon-bearing materials which have been formed through organic processes within the past 70,000 years. The method was developed by Willard F. Libby and associates at the Institute of Nuclear Studies of the University of Chicago in 1947. The first radiocarbon dates were announced by Libby in New York in 1949, and in 1960, he was awarded a Nobel Prize for his work in developing the method. Radiocarbon dating is extremely valuable in geology, archaeology and other fields, and can be used to date such materials as wood, peat, soil, grasses and leather as well as bone, shell and marls.

BACKGROUND

Radiocarbon or carbon-14* is one of three naturally occurring isotopes of carbon. Of the three (C-12, C-13, C-14) only carbon-14 is radioactive, which means that it decays over a period of time to nitrogen through emission of a beta particle.

Naturally occurring carbon-14 is produced in the earth's upper atmosphere by the action of high-energy neutrons formed by cosmic rays entering the earth's atmosphere. These neutrons react with the nuclei of nitrogen atoms to form carbon-14, according to the following formula:

$$\text{neutron} + N^{14} \rightarrow C^{14} + H^{1}$$

In essence, a neutron enters a nitrogen nucleus containing 7 neutrons and 7 protons, and knocks out one of the protons, leaving 6 protons and 8

---

*The terms radiocarbon, carbon-14, C-14, C^{14} and ^{14}C will be used interchangeably in this paper, as is also done in the literature.

neutrons. Because this new atom now has 6 protons, it acquires the characteristics of carbon, and unites with oxygen to form carbon dioxide. The new carbon atom, however, differs from regular carbon-12 in two significant ways. First, it is slightly heavier than C-12, and, more important, it is radioactive, which means that it is unstable and will eventually revert to nitrogen through emission of a beta particle.

The carbon dioxide formed by C-14 atoms is mixed with the troposphere, biosphere and oceans, and becomes part of an equilibrium system. It is assimilated by plants during photosynthesis and is later ingested by animals and humans as part of the food chain. All living organisms thus contain carbon-14.

While an organism is alive, it continues to take in additional carbon-14, eventually establishing an internal equilibrium with the C-14 being lost through radioactive decay. Because the rate of production of carbon-14 in the upper atmosphere can be assumed to be constant, as well as the rate of mixing with the earth's dynamic reservoirs, the internal equilibrium of living organisms can also be assumed to be constant over time and place on the earth. All living organisms therefore contain the same proportion of carbon-14.

When an organism dies, its intake of C-14 stops, and its proportion of carbon-14 falls at a given rate. This rate is equal to the rate of radioactive decay of C-14. If this rate is known, then the age of the organic material can be found by determining the amount of carbon-14 left at a given point in time. This is the basis of the radiocarbon dating method.

THE METHOD

Two problems had to be solved before radiocarbon dating could

become a practical reality. First, a method of measuring the low-level beta emissions produced by the decay of carbon-14 had to be developed. The method developed by W.F. Libby and associates (16) was called a screen-wall counter, consisting basically of Geiger counter surrounded by a massive shield of steel and a ring of anticoincidence counters.

In using the screen-wall counter, samples to be measured were first converted to solid carbon. The basic weaknesses of this system were the self-absorption of β-rays and the likelihood of absorption by the solid carbon of radioactive contamination, especially from atomic bombs being tested in the atmosphere at that time. (20). It was because of these weaknesses that the two methods currently used were developed. These two methods are the gas-proportional method using pure carbon dioxide, methane and acetylene; and the liquid scintillation counting of benzene. The latter method was first developed at the University of Texas Radiocarbon Laboratory and will be discussed in some detail later.

The second problem which had to be solved to make radiocarbon dating a reality was finding the rate of decay, as expressed by the half-life, of carbon-14. The value for the half-life determined by Libby and associates was 5,568 $\pm$ 30 years (16). This value became the established standard and although experiments at three labs in 1961 resulted in a more accurate average of 5,730 $\pm$ 40 years (2), the "Libby half-life" continues to be the basis of dates reported in the literature. This ensures uniformity of the data reported, while conversion to the more accurate base is done by simply multiplying by a factor of 1.03.

LIMITATIONS OF THE RADIOCARBON METHOD

Although the radiocarbon method is based on sound theoretical principles, it is not without its limitations. These limitations fall

into two categories: 1) Measurement uncertainty and 2) Errors in the assumptions on which the method is based.

Measurement uncertainty is due partly to the spontaneous nature of beta emission. Although in the long run, radioactive decay occurs at a known rate, the emissions occur at random and vary over short periods of time. This problem is dealt with by testing samples for periods of from one to ten days. And in cases where a sufficient amount of the sample is available, a second separate test is run as a method of controlling the statistical uncertainty. The remaining uncertainty is expressed as the statistical error in quoting the age, eg., 10,000 ± 30 years B.P.

A second type of measurement error arises from variations in counter efficiency and variations in counter background. These are controlled by periodically running control samples of radioactively dead materials.

A final type of measurement error is due to contamination of samples or improper interpretation of results. The former can be minimized by careful collection of samples in the field and by pretreatment in the radiocarbon lab. The latter problem depends upon the scientist in the field -- careful analysis of the archaeological and/or geological context must be made in all cases to avoid misinterpretations of results.

Errors in the basic assumptions on which the radiocarbon dating method is based present a more complex and less controllable situation. The assumption that the amount of radiocarbon in the atmosphere is constant is one which has been questioned. Possible causes of variations in the radiocarbon concentration are a lag in the mixing rate of C-14 between the oceans and the atmosphere, isotopic fractionation between various carbon compounds, and the release of reservoirs of older carbon which has been dormant. An additional problem is that the intensity of cosmic

radiation reaching the earth's upper atmosphere may also have varied over time. Factors thought to have caused this variation are explosions of supernovae, changes in the intensity of the earth's magnetic field and sunspot activity.

Two sources of recent fluctuations in the radiocarbon concentration are fossil-fuels and nuclear weapon testing. The use of fossil fuels, prominent since the industrial revolution, releases carbon into the atmosphere which has long since been radioactively "dead" and has the effect of diluting the natural C-12/C-14 ratio. Nuclear weapon testing before 1962 had the opposite effect. It is estimated to have increased the C-14 in the world by about 3%.

RADIOCARBON AND OTHER CHRONOLOGIES

Correlation with other chronologies has proven an excellent way of testing the validity of the radiocarbon chronology and has also provided the means of making some corrections. The greatest amount of work done in this respect has been in the area of dendrochronology or tree-ring dating. Study at the Tree-Ring Research Laboratory of the University of Arizona has produced an 8200-year chronology. (6) Measurements on rings from this chronology have been made by three radiocarbon laboratories, at the University of Arizona, the University of California and the University of Pennsylvania. There is excellent agreement among the labs on the averages and all three have noted a significant long-term deviation of C-14 dates from tree-ring dates for the earlier B.C. millennia as well as possible short-term variations. As a result of these tests, Hans E. Suess of the La Jolla Laboratory produced a calibration curve which can be used to correct radiocarbon dates to about 3000 B.P.

Other chronologies which have proven useful in confirming and/or correcting the radiocarbon chronology are the Egyptian historical and

the varve chronologies. Both of these have tended to support the results of the dendrochronological correlation.

The correlation of radiocarbon dates with the Egyptian chronology has been of particular interest to archaeologists, because the materials tested are more representative of those found in archaeological excavations than the wood of the bristlecone pine used in the tree-ring correlations. Examples of radiocarbon results for historically dated Egyptian samples are given with the illustrative material following this section.

Varve chronologies are produced by counting the pairs of layers (varves) of alternately coarse and fine silt or clay believed to comprise an annual cycle of deposition in still bodies of water. This has been done extensively in Sweden using the clays which originated in lakes fed by melting glaciers. A problem in attempting to correlate the varve and radiocarbon chronologies is due to the negligible amounts of organic carbon usually found in varves. Varve sequences have been successfully related to radiocarbon through associated pollen sequences, however, and tend to be in general agreement with the dendrochronological data.

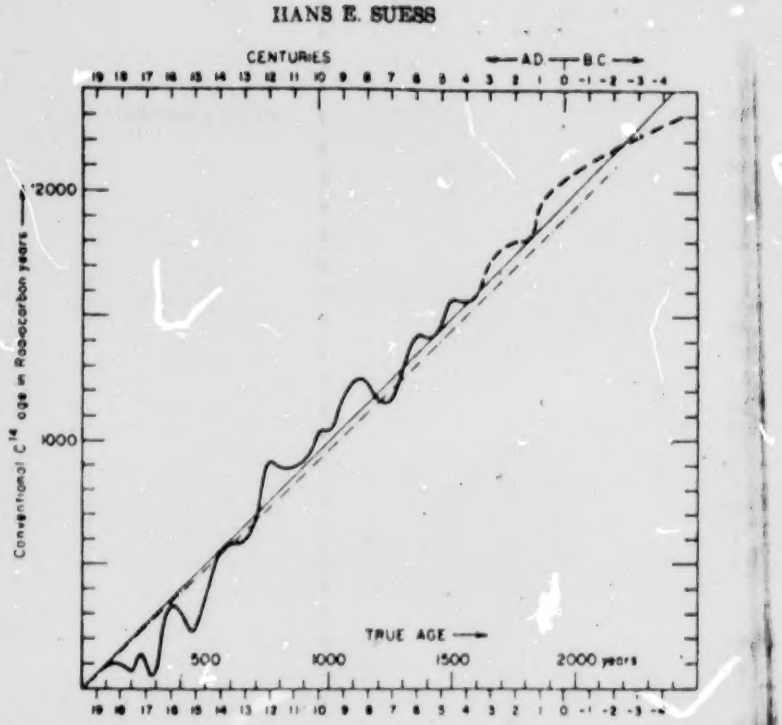
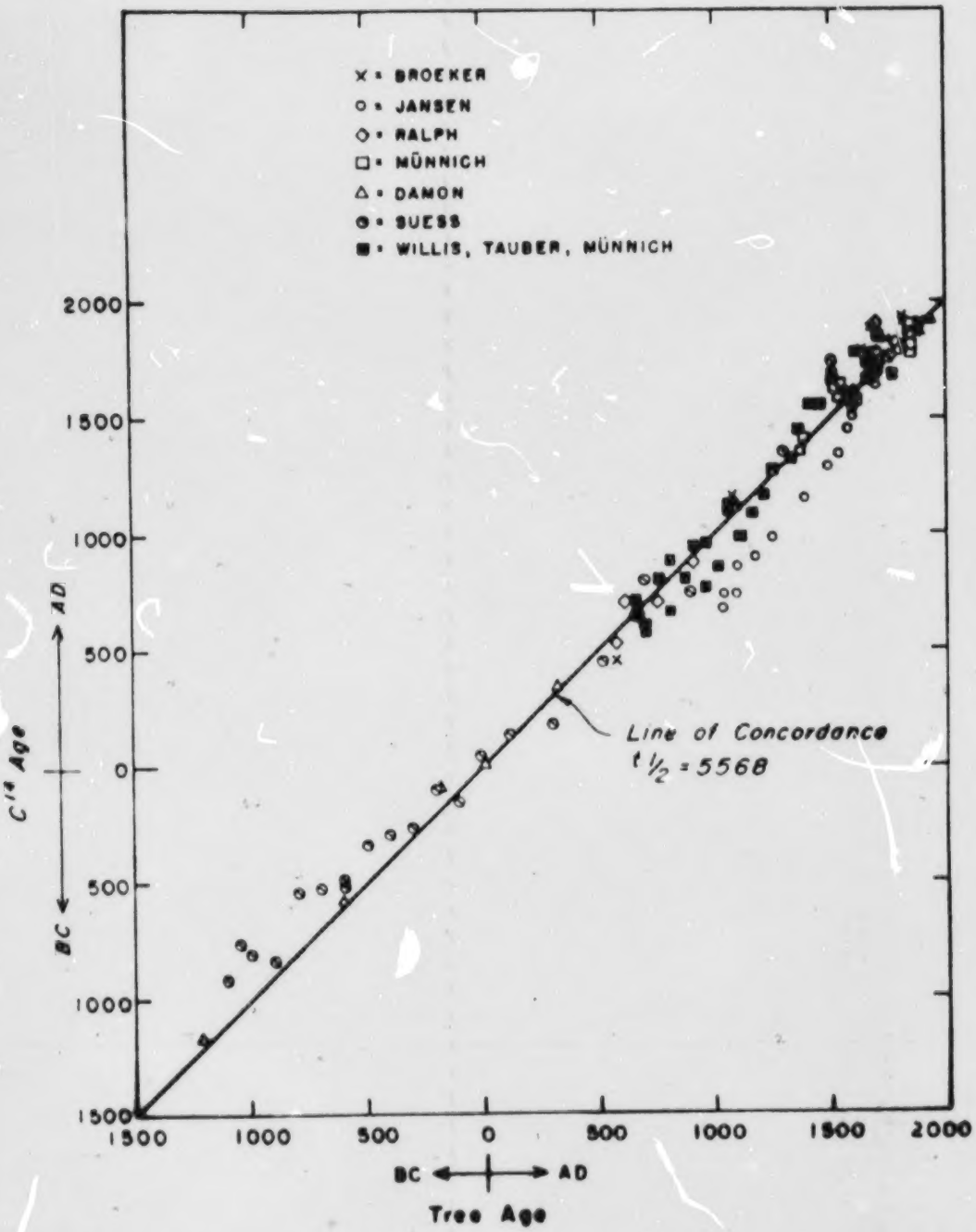


Fig. 4. Approximate empirical relationship between conventional radiocarbon dates (assuming $T_{1/2}$ = 5568 years) and dendrochronologically determined wood ages as derived from La Jolla ΔC^{14} determinations. The diagonal broken line refers to data calculated with a C^{14} half-life of 5730 years.

This is the famous calibration curve developed by Hans Suess for converting radiocarbon dates to dendrochronologically correct ones. (63)



An intercomparison of tree-ring studies, comparing tree-ring age with radiocarbon age. (60)

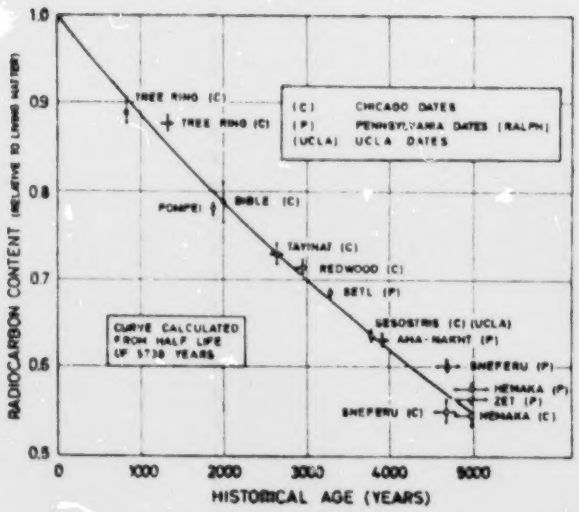


FIG. 10. Samples of known age

LIBBY

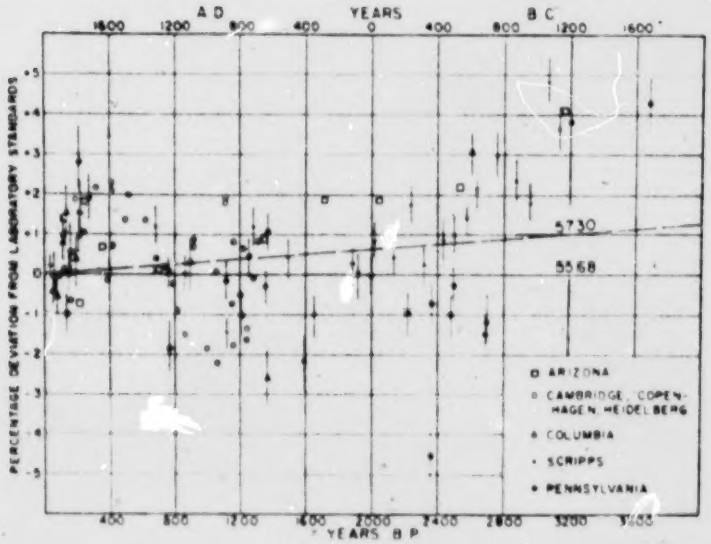


FIG. 9. Some tree-ring-dated samples

Two graphs comparing radiocarbon ages and historical ages, and radiocarbon ages and tree-ring dates (14)

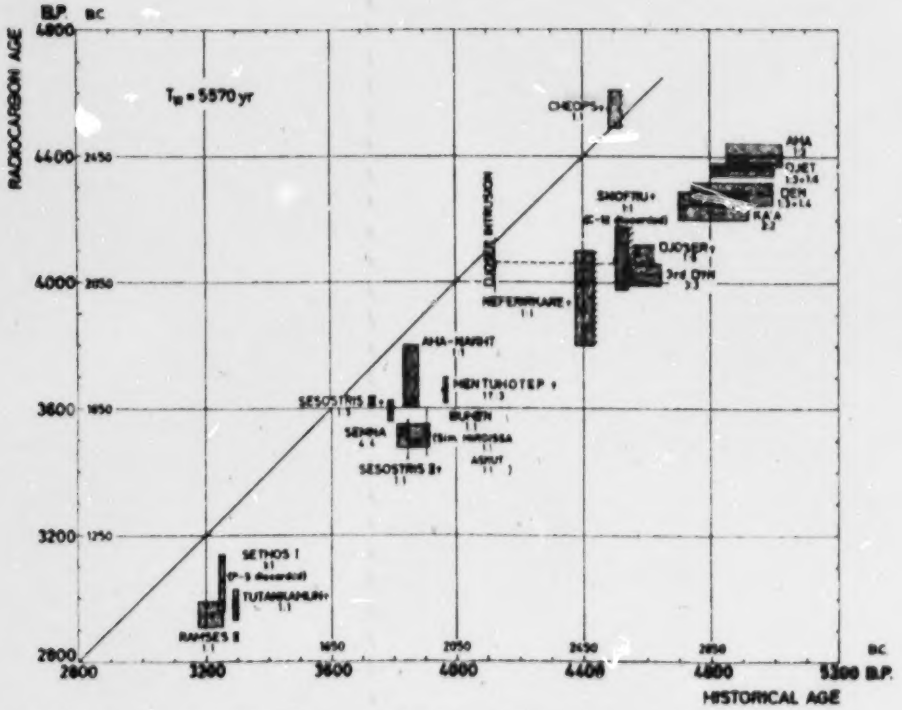


Fig. 3. Distribution of C 14-dated samples from Egypt. The maximum and minimum limits of the historical dates are indicated. The C 14 dates are weighted averages. The numbers indicate the number of samples and laboratory values.

An example of correlation of radiocarbon and historical ages of samples from Egypt. (83)

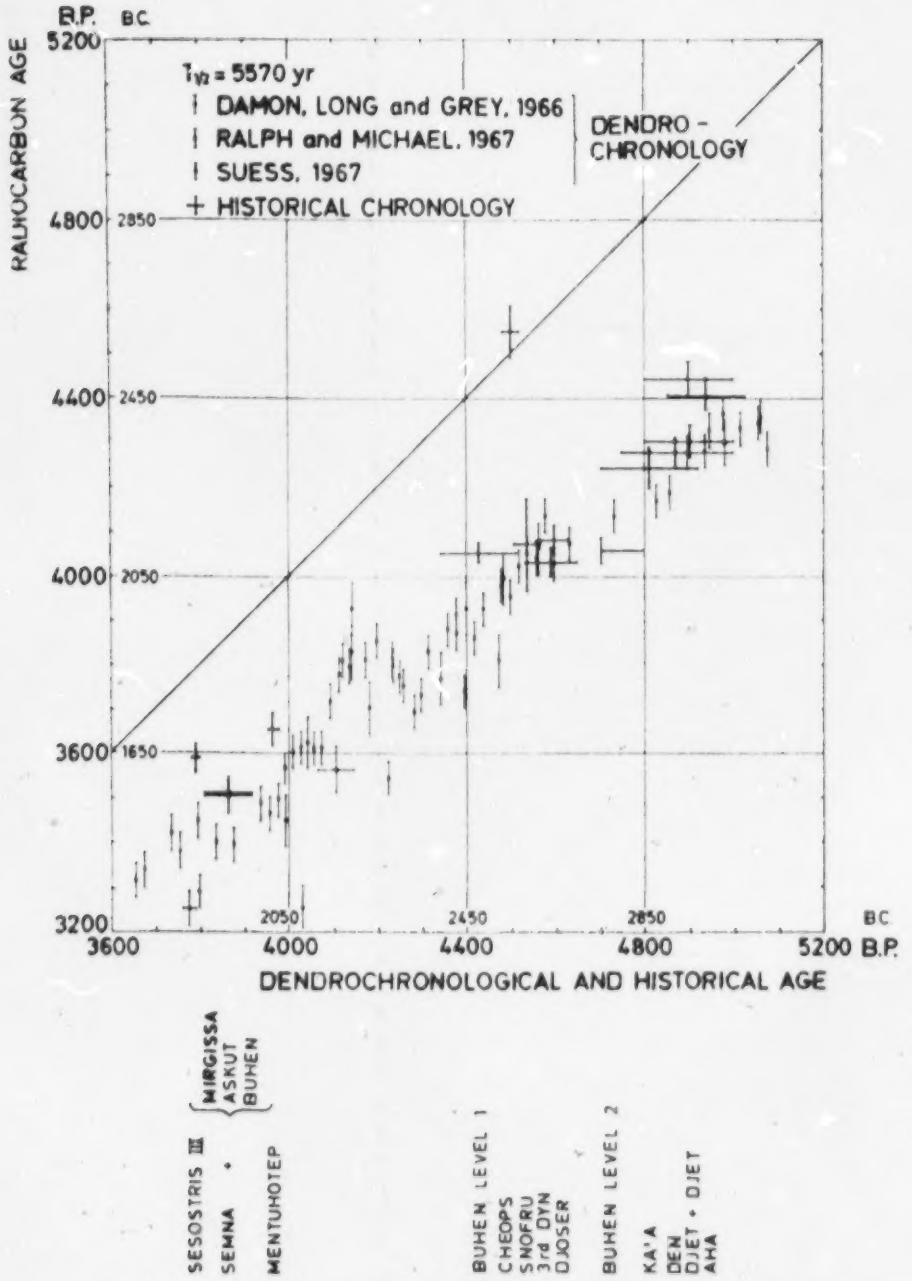


Fig. 4. A comparison between the C 14/C 12 deviations measured by using Egyptian samples reliably dated historically and the deviations measured by using dendrochronologically dated samples. All dates are calculated with the half-life of 5570 years.

An example of a comparison of dendrochronological, historical and radiocarbon ages. (83)

VISIT TO U. T. RADIOCARBON LABORATORY

"If we enter a radiocarbon laboratory today - and there are several dozen of them over the globe - we feel as if we are stepping into the quarters of one of those monstrous mad scientists of the movies who, surrounded by mysterious and intricate gear, are preparing the downfall of a government or of the whole human race.

"One entire room in such a laboratory seems to consist of nothing but glass and metal pipes, cylinders, conduits, intertwined in the weirdest shapes. And these pipes are steaming and hissing; liquids and gases rise up and go down; the pointers of meters quiver under invisible influences."

C.W. Ceram, in The First American: a Story of North American Archaeology (Harcourt, 1971)

The highlight of my research for this paper was, without any doubt, my visit to the University of Texas Radiocarbon Laboratory at the Balcones Research Center. There I was given a fascinating tour of the facilities as well as detailed explanations of the procedures which are carried out in radiocarbon dating. At this point, I will briefly describe these procedures. My sources of information are my own notes and a four-page summary of the procedures which was compiled by Mr. Valastro, associate director of the lab.

The U.T. Radiocarbon lab carries out the radiocarbon dating process by the liquid scintillation method, using benzene as the counting liquid. It is therefore necessary to convert all samples to be tested to benzene. First, however, the samples are pretreated to remove contaminants.

Samples which can be tested include organic materials such as wood, peat, charcoal, leather or any other material containing bonded carbon. Inorganic materials which can be tested are such things as shell, bone, caliche and marl, all of which are formed by living organisms. The amount of sample required varies according to the type of material but rough estimates are as follow:

ORGANIC MATERIALS	
Clean charcoal	6 gm.
Clean peat	10-12 gm.
Wood	8-10 gm.
INORGANIC MATERIALS	
Carbonates in general	35-40 gm.

Pretreatment of the samples involves acid treatment for both organic and inorganic samples, plus visual screening of organic materials

with low power magnification to remove rootlets.

The next step is the synthesis of benzene for testing using the carbon contained in the sample. Organic samples are burned in a vacuum by the addition of oxygen to produce carbon dioxide. Carbon dioxide is evolved from inorganic samples by treatment with hydrochloric acid. Once the carbon dioxide has been produced, the steps are the same for all samples.

Conversion of the CO_2 to benzene involves three steps. First the CO_2 is introduced into a reaction vessel containing molten lithium at 400° C, producing lithium carbide as one product.

The lithium carbide is then brought to room temperature and hydrolized by the addition of distilled water. This produces acetylene gas, which is screened for impurities and measured for yield.

The final step is to introduce the acetylene into a catalyst which converts it to benzene by a process called trimerization. The lizuid benzene is then collected, measured and frozen in a storage vial until it is ready to undergo the scintillation process to determine its radioactivity.

The processes involved in the synthesis can be summarized as follows:

$$\text{organic sample} + O_2 \rightarrow CO_2$$

$$\text{inorganic sample} + HCl \rightarrow CO_2$$

$$2CO_2 + 10Li \rightarrow Li_2C_2 + 4LiO$$

$$Li_2C_2 + H_2O \rightarrow C_2H_2 + 2LiO$$

$$3H_2C_2 \dashrightarrow C_6H_6$$

The actual radiocarbon assay of the benzene is done by counting the beta emissions produced by the decay of C-14 atoms and then comparing the count with the count of a sample of known age.

The U.T. Radiocarbon lab has three liquid scintillation counters. A vial of 3 ml. of benzene and 1 ml. of scintillation fluid is placed in one of the counters. The scintillation fluid causes the production of a photon of light every time a beta particle is emitted by the breakdown of a C-14 atom in the benzene. These photons of light are picked up by two very sensitive photomultipliers which create an electric pulse that is then counted by an automatic recorder.

Samples are generally counted for 1400 minutes (approx. 24 hrs.). Once the counting of the sample is completed, the average count per minute is calculated and compared with the count for a sample of known age. The standard used in this case is a Natural Bureau of Standards oxalyic acid, which is 95% active and shows an activity of 8.70 counts per minute per gram. The Libby half-life is used in calculating dates. Radiocarbon dates determined by the lab are expressed in years B.P. (before present) and the "present" reference year used by international agreement is 1950. Examples of work sheets can be seen in the appendices following this section.

The dates which are determined by the radiocarbon lab are recorded and reported periodically to the journal, Radiocarbon. Radiocarbon, which began in 1959 as the Radiocarbon Supplement of the American Journal of Science, is the international vehicle for reporting radiocarbon dates. An example of U.T. dates as they appeared in Radiocarbon is appended. Radiocarbon also provides a list of radiocarbon labs active throughout the world; this list appears in the final issue each year. The most recent list, from Radiocarbon, v. 18, no.3 (Dec. 1976) is appended.

University of Texas Radiocarbon Laboratory

23.

COUNTING DATA

Date 10/18/76 x-Background Run No. 2348

Sample Name _____

WEIGHING OPERATIONS: SAMPLE VIAL CODE "D"

VIAL + SAMPLE 67.7005 = _____ ml. BENZENE

VIAL 65.0812 = _____ gms. CARBON

WT. SAMPLE _____ gms

VIAL + MIX 68.5973 C^{14} Ref: 33.304×10^3

VIAL 65.0812 33.356×10^3

WT. MIX _____ _____

MDN: 33.330×10^3
9.10

COUNT RATE:

RED	GREEN	RED	GREEN
644		601	
665		665	
728		688	
617		640	
701		646	
623		614	
688		648	
665		686	
646		622	
644		646	
606		607	
685		652	
649		664	
650		655	
681		601	
665		666	
663		654	
640		663	
652		651	
643		605	
TOTAL COUNT	26397		
TOTAL TIME	4000		

RED COUNT RATE $6.60 \pm .04$ GREEN COUNT RATE _____

Sample of worksheet used in U.T. Radiocarbon Laboratory

cinders overlying charcoal horizon; otherwise open to top of lava flow, which may be one of latest flows in area.

Crystal Ice Cave series

Charred roots projecting from soil beneath lava flow at entrance to Crystal Ice Cave (Kings Bowl on some maps), 29 km W of Aberdeen, Idaho (42° 56′ N Lat, 113° 15′ W Long), ca. 65 km SE of Craters of the Moon. From same area is sample dated 2130 ± 130 (Prinz, 1970, p. 946, citing Edwin Olson). This is 1st lava flow from Great Rift. Samples were ca. 0.5 m apart and may be from same plant.

Tx-1164. Crystal Ice Cave, 2-8 — **2090 ± 470**, **140 B.C.**

Tx-1165. Crystal Ice Cave, 2-9 — **2360 ± 150**, **410 B.C.**

General Comment on Craters of the Moon (F.M.B.): close grouping of all dates around 2200 yr B.P. suggests not only that this is valid date but also that final activity from Great Rift took place through much of its extent.

D. Lava Flow, Utah

Tx-1166. Cinder Cone, Utah, 2-10 — **660 ± 170**, **A.D. 1290**

Root fragments, not charred, in old soil layer beneath lava flow in Cold Tunnel at Cinder Cone, 11.3 km W of Fillmore, Millard Co., Utah (38° 59′ N Lat, 112° 28′ W Long). Roots appear unrelated to present vegetation; thus may date lava flow. Area is ca. 500 km S of Craters of the Moon, above, and is independent center of recent volcanic activity. General appearance suggests same age as Craters of the Moon lava. Coll. 1970 and subm. by F. M. Bullard. *Comment* (F.M.B.): age much more recent than Craters of the Moon samples; must await further confirmation.

E. Bermuda

Bermuda stratigraphy series

Land snail samples (*P. bermudensis zonatus*) from various locations on Bermuda, dated to assist completion of stratigraphy of Bermuda (Land *et al.*, 1967). Coll. by S. J. Gould, Harvard Univ.; subm. by L. S. Land, Dept. Geol. Sci., Univ. of Texas, Austin. δC^{13} values relative to PDB III, standard notation and corrections applied.

Tx-1071. Whalebone Bay, L-1034G — **18,250 ± 450**, **16,300 B.C.**

$\delta C^{14} = -897 \pm 2.6‰$ $\delta C^{13} = -9.9‰$

From nonlithified pocket a few cm above "disappearing" red soil, NE end of r.r. cut just E of Yellow Fever Graveyard, St. George's I. (32° 21′ 54″ N Lat, 64° 42′ 42″ W Long); represents latest eolianite activity (Southampton) on St. George's I.

Tx-1072. McGall's Hill, L-1034R — **21,460 ± 530**, **19,510 B.C.**

$\delta C^{14} = -931 \pm 2.6‰$ $\delta C^{13} = -8.0‰$

From uppermost nonlithified zone, Southampton Fm, type Saucos Hills sec. for Bermudian stratigraphy (32° 18′ 15″ N Lat, 64° 44′ 15″ W Long).

Tx-1073. Bermuda L-1034D — **24,720 ± 800**, **22,770 B.C.**

$\delta C^{14} = -954 \pm 2.6‰$ $\delta C^{13} = -10.1‰$

From youngest dunes, in commercial sand quarries, SW end of Bermuda (32° 15′ N Lat, 64° 51′ W Long).

Tx-1074. Bermuda L-1034E,F,H,K — **23,900 ± 1270**, **21,950 B.C.**

$\delta C^{14} = -949 \pm 2.6‰$ $\delta C^{13} = -8.5‰$

Combined sample from various localities in uppermost dune ridge, N shore St. George's I. (32° 21′ N Lat, 64° 44′ W Long); probably Pembroke in age.

Snail study series, Bermuda

Snail shells coll. to study possible ingestion of dead carbon from limestone environment, affecting age measurement. Coll. 1970 by S. J. Gould and subm. by L. S. Land.

TX-1218. Bermuda S-R1 $\delta C^{14} = +92 \pm 11.2‰$

Recent snails living on red soil behind Biological Sta., St. George's West (32° 20′ 00″ N Lat, 64° 43′ 12″ W Long).

Tx-1219. Bermuda S-R2 $\delta C^{14} = +347.2 \pm 16.0‰$

Recent snails living on red soil in field adjacent to Perfume Factory (32° 20′ 57″ N Lat, 64° 42′ 57″ W Long).

Tx-1220. Bermuda S-P1 — **26,440 ± 970**, **24,450 B.C.**

Snail shells from Shore Hills Soil as exposed in Government Quarry (32° 20′ 36″ N Lat, 64° 42′ 27″ W Long). Soil overlain by rocks dated by U/Th^{230} as 120×10^3 yr (Land *et al.*, 1967).

General Comment (L.S.L.): δC^{13} values of Tx-1071-Tx-1074 are typical for soil atmosphere and for very old Bermuda limestones; snails may obtain HCO_3 from underlying limestones, and ages may be too old. Tx-1218 and Tx-1219 negate this premise, as they indicate Recent snail shells have positive δC^{14} values; these ages are minima. Tx-1220, from shells have positive δC^{14} values; these ages are minima. Tx-1220, from shells >120,000 yr old, indicates contamination by Recent carbon, possibly from incipient recrystallization. Thus, dates indicate Southampton Formation is >20,000 yr old.

F. Coral Reef Studies, Jamaica

Samples from coral reefs, just W of ship channel, Discovery Bay, Jamaica (18° 28′ 06″ N Lat, 77° 24′ 48″ W Long). Coll. 1969 and subm. by L. S. Land, Dept. Geol. Sci., Univ. of Texas, Austin.

[RADIOCARBON, VOL. 18, NO. 3, 1976, P. 376-387]

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* Inactive Laboratories

[1] The [3]H—Laboratorium of this institute (directed by Klaus Fröhlich) should be addressed separately.

[14] Lists from this laboratory have not been submitted to RADIOCARBON. See Gdansk I, Acta Physica Polonica, vol 22, p 189, 1962 Gdansk II, *ibid*, vol 32, p 39, 1967.

[3] This designation Gif supersedes both Sa (Saclay) and Gsy (Gif-sur-Yvette). The only Gsy date list to be published is Gsy I (Coursaget and Le Run, RADIOCARBON, v 8).

[4] From January 1, 1961 the Gro numbers have been replaced by GrN numbers. "New" dates are referred to the NBS oxalic-acid standard.

[5] Early dates from this laboratory were given a code designation that represents the name of the sponsoring institution, e g, I (AGS) for American Geographical Society (Heusser, RADIOCARBON SUPPLEMENT, v 1).

[6] Formerly Hazelton Nuclear: code designation HNS has been dropped.

[7] Some dates from this laboratory were published with the code designations S (Pringle *et al*, 1957, Science, v 125, p 69-70).

[8] See SM.

[9] See Gif.

[10] Some dates from this laboratory have been published with the code designation RC (Flint and Gale, 1958, AM JOUR SCI, v 256, p 698-714). The code designation MP published in volume 1 of the RADIOCARBON SUPPLEMENT (1959, p 216) has been changed to SM in conformity with the wishes of the laboratory, and is explained by the change of the company's name from Magnolia Petroleum Company to Socony Mobil Oil Company, Inc.

[11] Formerly Texas-Bio-Nuclear, then Kaman Instruments. The laboratory is no longer operating.

[12] Moved to Ahmedabad. See PRL.

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1. Anderson, E.C., W.F. Libby and others. "Natural Radiocarbon from Cosmic Radiation." Physical Review 72 (Nov. 15, 1947): 885-89.

   A detailed description of the first successful attempt to detect the presence of natural carbon-14 in living matter is given. This was achieved through enrichment of biological methane, raising activity to levels convenient for counting. The counting was done with large Geiger-Muller counters.

2. Godwin, H. "Half-life of Radiocarbon." Nature 195 (1962): 984.

   The resolutions adopted by the Fifth Radiocarbon Dating Conference at Cambridge regarding the half-life of radiocarbon are reported. It was decided to accept the mean of the values determined by three research groups, 5,730 ± 40 years, as the best value available. It was also decided, however, that radiocarbon age results will continue to be reported on the basis of the "Libby half-life" or 5,568 years.

3. Mann, W.B., W.F. Maslow and E.E. Hughes. "Half-life of Carbon-14." International Journal of Applied Radiation and Isotopes 11 (1961): 57-67.

   Experiments conducted at the National Bureau of Standards to redetermine the half-life of C-14 are described. Methods and technical difficulties encountered are described in detail. On the basis of thorough analysis of results, the half-life is estimated to be 5760 ± 50 years.

4. Olsson, I.U. and I. Karlén. "The Half-life of C^{14} and the Problems Which are Encountered in Absolute Measurements of β-decaying Gases." In Proceedings of the Symposium on Radioactive Dating, Athens, 1963, pp. 3-11. Vienna: International Atomic Energy Agency, 1963.

   A report of the redetermination of the half-life of radiocarbon which was performed at the University of Uppsala, Sweden, is presented. A proportional counter was used for the measurements, which are described in detail. The redetermination resulted in a value of 5685 ± 35 years for the half-life of C^{14}.

5. Watt, D.E., D. Ramaden and H.W. Wilson. "Half-life of Carbon-14." International Journal of Applied Radiation and Isotopes 11 (1961): 68-74.

   The redetermination of the half-life of C-14 using mass spectroscopy and proportional counting done at the lab at Aldermaston is described. The new value obtained is 5780 ± 65 years.

II. RADIOCARBON DATING - GENERAL

6. Aitken, M.J. "Radiocarbon Dating." In Aitken, M.J., Physics and Archaeology, pp. 26-84. Oxford: Clarendon Press, 1974.

An excellent, comprehensive treatment summarizing developments in all aspects of radiocarbon dating as reported in the literature since 1949.

7. Barker, H. "Critical Assessment of Radiocarbon Dating." Philosophical Transactions of the Royal Society, Series A, 269 (1970): 37-45.

A review of the many and comples factors which affect the accuracy of radiocarbon dates is presented. The major recommendations include (1) the need for closer collaboration between the archaeologist and the scientist in the dating lab, and (2) the widespread adoption of the liquid scintillation technique which will allow for increased output of dates at reduced cost, without reducing the standards of accuracy in the dates.

8. Burleigh, R. "The New Zealand Radiocarbon Conference." Antiquity 47 (1973): 54-56.

The 8th International Conference on Radiocarbon Dating, held at Lower Hutt City, Wellington, New Zealand, 18-25 October 1972 is described. A total of 120 participants from physics, chemistry, geology, geochemistry, soil science, archaeology and other disciplines attended. The primary aim of the conference was to bring together a significant proportion of the scientists actively engaged in operating radiocarbon dating laboratories, to discuss technical and methodological aspects of radiocarbon dating. It was decided that the conventional 5570 year "Libby" half-life should continue to be used.

9. Davis, E.M. "Interdisciplinary Appraisal of Radiocarbon Dates in Archaeology." In Proceedings of the Sixth International Conference: Radiocarbon and Tritium Dating, Pullman, Washington, 1965, pp. 294-303.

The head of the University of Texas Radiocarbon Laboratory presents an elegant statement of the need for closer working relations between archaeologists and radiochemists in the dating laboratories. The process of radiocarbon dating must be viewed as a joint analysis of mutual problems instead of a mere impersonal exchange of information, for there to be meaningful results achieved.

10. Godwin, H. "Carbon-14 Dating: Symposium in Copenhagen." Nature 174 (1954): 868.

A summary of the Carbon-14 Symposium held in Copenhagen Sept. 1-4, 1954. This was the first joint meeting of

radiocarbon researchers held in Europe. Discussions focused mainly on the methods of counting in use at that time: the solid-carbon methods developed by Libby, and the gas-counting methods using CO_2 and acetylene. Brief mention was made of the liquid scintillation method. Sources of error and the problem of standardization of form of publishing results were also discussed.

11. Godwin, H. "Radiocarbon Dating: Fifth International Conference." Nature 195 (1962): 943.

A report describing the fifth radiocarbon conference, which was held at the University of Cambridge, 23-28 July 1962. The conference was attended by representatives of more than 30 radiocarbon labs, including those newly established in Poland and Yugoslavia. Alternative methods of counting were presented as well as three reports from labs involved in redetermining the half-life of C-14. Other topics covered include dendrochronological and Egyptian calibration of radiocarbon dates and field applications of radiocarbon dating.

12. Hole, F. and R.F. Heizer. "Radiocarbon Dating." In Hole, F. and R.F. Heizer, An Introduction to Prehistoric Archeology, pp. 251-258. New York: Holt, Rinehart & Co., 1973.

A brief introduction to the radiocarbon dating method for beginning archaeology students is given.

13. Johnson, F. "A Bibliography of Radiocarbon Dating." American Journal of Science Radiocarbon Supplement 1 (1959): 199-214.

A comprehensive bibliography on radiocarbon dating, covering materials published through 1959. Of particular importance is the list of dates reported in other journals before the Radiocarbon Supplement was begun. Also included are numerous articles on the development of the method, interpretation of dates, both from geological and archaeological literature.

14. Libby, W.F. "History of Radiocarbon Dating." In Radioactive Dating and Methods of Low-Level Counting, pp. 3-25. Vienna: International Atomic Energy Agency, 1967.

A detailed history of the development of radiocarbon dating is given. Discussed in historical perspective are the advent of low-level counting, isotopic enrichment, the fossil fuel or "Suess" effect, determination of the new half-life, the proliferation of measurement techniques and the impact of archaeological insight upon the validity of radiocarbon dates.

15. Libby, W.F. "Radiocarbon Clock." Chemical Technology 3 (1973): 142-144

A description of the carbon cycle is given, including information concerning the formation and incorporation of radiocarbon into the cycle. The long lifetime of radio-

carbon is cited as the reason that the mixing of C-14 into the atmosphere and oceans is complete, and thus why the amount of C-14 can be assumed to be relatively constant throughout the world.

16. Libby, W.F. Radiocarbon Dating. Chicago: University of Chicago Press, 1952, 1955.

This book is the seminal work in the field; the first edition appeared in 1952. Covered are the principles of the radiocarbon dating method, worldwide distribution of radiocarbon, the half-life of radiocarbon, and the preparation and measurement of samples. An extensive list of dates reported prior to the fall of 1954 is also included in the second edition. This edition also reports the change in the accepted half-life of C-14 and the development of the gas proportional counter for measuring the radiocarbon content of samples.

17. Libby, W.F. "Radiocarbon Dating." Philosophical Transactions of the Royal Society, Series A, 269 (1970): 1-10.

A detailed review of the historical development of radiocarbon dating. Two facts learned through long experience with carbon-14 dating are: (1) for simultaneous dating, it is reliable; however, (2) on absolute dates, it can be incorrect by as much as 600-700 years.

18. Olsson, I.U. "Modern Aspects of Radiocarbon Dating." Earth Science Reviews 4 (1968): 203-218.

The radiocarbon method is discussed and recent developments in the fixing of the half-life of C-14 are reviewed. The occurrences and causes of variations in the C-14/C-12 ratio are outlined, as are the possibilities and influences of contamination. Includes excellent graphic illustrations.

19. Ralph, E.K. "Carbon-14 Dating." In Michael, H.N. and E.K. Ralph, Dating Methods for the Archaeologist, pp. 1-48.

A lengthy treatment including development of the radiocarbon dating method, problems associated with samples of various types of materials and methods of collection, packaging, labelling and description of samples. There is also a brief discussion of the publication Radiocarbon and the McBee Edge-Punched Cards, plus a section on the interpretation of C-14 dates and detailed coverage of laboratory methods.

20. Ralph, E.K. and H.N. Michael. "Twenty-five Years of Radiocarbon Dating." American Scientist 62 (1974): 553-60.

An excellent, detailed treatment concentrating on the problem of variations in the amount of radiocarbon in the atmosphere and the means of correcting this problem.

Beginning with a discussion of the development of the method, it also includes the chemical reactions and statistical problems involved in the method. Tree-ring calibration is presented as the primary and most precise method of correcting radiocarbon dates. Other methods discussed are varve chronology, ice core correlation and comparison with the chronologies of ancient civilizations.

21. Watkins, T. and D.D. Harkness. "Handlist of Radiocarbon Laboratories." In Watkins, T. Radiocarbon, Calibration and Prehistory, pp. 136-143. Edinburgh: The University Press, 1975.

A list of known active radiocarbon laboratories which are open in at least some circumstances to archaeologists. This list gives (a) some indication of the ability or willingness of the laboratories to undertake archaeological dating; (b) a statement from each laboratory concerning the special services it may offer; (c) the likely time taken to obtain a C-14 date; and (d) a scale of charges.

22. Willis, E.H. "Radiocarbon Dating." In Brothwell, D. and E. Higgs, ed., Science in Archaeology, pp. 46-57. London: Thames and Hudson, 1969.

A brief but technical discussion of the fundamental assumptions of the radiocarbon method and the effects of deviations from these assumptions on the accuracy of the dates. Effects of isotopic fractionation, fossil fuel and thermonuclear weapon testing are among items discussed. A brief review of counting methods and sources of radiocarbon dates are also included.

III. LABORATORY METHODS

23. Buddemeier, R.W. and others. "Improved System of Methane Synthesis for Radiocarbon Dating." Review of Scientific Instruments 41 (1970): 652-4.

Consists of a description of an improved design for the hydrogenation converter used to convert CO_2 to methane for use in radiocarbon dating. This innovation improves efficiency of the process, in terms of both time and yield.

24. Burleigh, R. "Bomb Combustion of Radiocarbon Samples." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, pp. B1-B10. Wellington: Royal Society of New Zealand, 1972.

Evaluation and discussion of the bomb method for combustion of samples which has been developed at the British Museum laboratory. The method was devised as an alternative to the conventional tube furnace method, which is time-consuming and requires constant supervision. A serious explosion which occurred during a routine combustion was probably caused by fine sample material suspended in the bomb atmosphere. A safer version of the bomb has now been designed and put into use.

25. Crathorn, A.R. "Use of an Acetylene-Filled Counter for Natural Radiocarbon." Nature 172 (1953): 632.

An apparatus constructed in the Davy-Faraday Research Lab in London for the counting of natural radiocarbon in the form of acetylene is described. This method appears to be more efficient and offers greater scope for improvement than the screen-wall counter method employed by Libby

* 26. Currie, D.R. "Gas Counters and Counting." In Grant-Taylor, T.L. Radiocarbon Users Conference. Wellington, New Zealand: Department of Scientific and Industrial Research, 1971.

27. DeVries, Hl. and Barendsen, G.W. "Radiocarbon Dating by a Proportional Counter Filled with Carbon Dioxide." Physica 19 (1953): 987-1003.

The carbon dioxide-filled proportional counter developed at the Natuurkundig Laboratorium of Rijks University in Groninger, Netherlands is described. Reasons for developing this new counter include the laboriousness of sample preparation necessitated by and low efficiency of Libby's method.

28. DeVries, Hl., M. Stuiver and I. Olsson. "A Proportional Counter for Low-Level Counting with High Efficiency." Nuclear Instruments and Methods 5 (1959): 111-14.

Descriptions and comparison of two small counters developed in the C-14 dating laboratories in Groningen and Uppsala. Both were attampts at accomodating usual small amount of material available for testing.

29. Fairhall, A.W., W.R. Schell and Y. Takashima. "Apparatus for Methane Synthesis for Radiocarbon Dating." Review of Scientific Instruments 32 (1961): 323-25.

At the time this article appeared, gas proportional counting had become the favored technique for radiocarbon dating, with CO_2 the counting gas used by most labs. The apparatus described here converts any given quantity of CO_2 to methane in one step using catalytic hydrogenation with a ruthenium catalyst. Advantages of methane over both CO_2 and acetylene are presented.

30. Geyh, M.A. "Comparison: Proportional Counter and Liquid Scintillation Spectrometer for Radiocarbon Dating." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, pp. B81-B93. Wellington: New Zealand Royal Society, 1972.

The two preferred radiometric techniques used in radiocarbon dating are compared in terms of theoretical and practical results. After discussing the advantages and disadvantages of both methods, the author concludes by pointing out that the specifications for the two techniques are so different that neither can be given a general recommendation. The working conditions of the C-14 laboratory should therefore be the determining factor in choosing the most suitable system.

* 31. Gough, K.J. "An Evaluation of Some Methods of Radiocarbon Counting." In Grant-Taylor, T.L. Radiocarbon Users Conference. Wellington, New Zealand: Department of Scientific and Industrial Research, 1971.

*32. Grant-Taylor, T.L. "Contamination of Radiocarbon Samples." In Grant-Taylor, T.L. Radiocarbon Users Conference. Wellington, New Zealand: Department of Scientific and Industrial Research, 1971.

* 32. Grootes, P.M., W.G. Mook and J.C. Vogel. "Enrichment of Radiocarbon for Dating Samples up to 75,000 Years." Zeitschrift Naturforsch 30A (1975): 1-14.

An explanation of the method of thermal diffusion isotopic enrichment by which the range of the radiocarbon dating method can be extended by about 20,000 years. A description of the Clusius-Dickel type enrichment columns and their operation is given. The combustion-, reduction- and oxidation-apparatus and their operation are described. (Physics Abstracts)

33. Harkness, D.D. "The Role of the Archaeologist in C-14 Age Measurement." In Watkins, T. Radiocarbon, Calibration and Prehistory, Appendix II. Edinburgh: The University Press, 1975.

This article attempts to clarify where and why the archaeologist can assist in the practical aspects of dating and in so doing also answers such familiar questions as: which sample material is most suited to the production of a valid C-14 date; how much material is required; how are samples best collected, recorded, stored and transported.

34. Haynes, C.V., Jr. "Radiocarbon Samples: Chemical Removal of Plant Contaminants." Science 151 (1966): 1391-92.

A description of a method of separating contaminating plant material from charcoal samples by nitration and acetone leaching. This is done following a preliminary treatment with sodium hydroxide and sodium hypochlorite.

35. Jeffreys, D., D. Larson and J.D. French. "Carbon-14 Dating with Nuclear Track Emulsions." American Journal of Physics 40 (1972): 1400-03.

A newly developed dating procedure employing nuclear emulsions is described. The advantages are modest cost, no need for electronic circuits and interdisciplinary nature. The sensitivity is such that samples of less than 0.2 grams of carbon can be assayed, providing an area of application not achieved by counter methods.

* 36. Kretner, R. and G. Dickel. "Enrichment of $^{14}CH_4$ by Thermal Diffusion for Use in Radiocarbon Dating." Zeitschrift Naturforsch 30A (April 1975): 554-60.

Use of a thermal diffusion column to extend the range of the radiocarbon dating method about 20,000 years is described. In order to calculate suitable dimensions and operational conditions, a theory of nonlinear enrichment is derived. (Physics Abstracts)

37. Noakes, J.E., S.M. Kim and J.J. Stipp. "Chemical and Counting Advances in Liquid Scintillation Age Dating." In Proceedings of the Sixth International Conference: Radiocarbon and Tritium Dating, Pullman, Washington, 1965, pp. 68-92. U.S. Atomic Energy Commission, Division of Technical Information, 1966.

A state-of-the-art report on the technique of benzene liquid scintillation in radiocarbon dating. Includes discussion of the chemistry involved in the method, a description of the reaction chamber used at Florida State University, and advances in detection and counting.

38. Nydal, R. "Proportional Counting Techniques for Radiocarbon Measurements." Review of Scientific Instruments 33 (1962): 1313-20.

A report from the Radiological Dating Laboratory in Trondheim, Norway, on the development of improvements in proportional counters used for radiocarbon measurements.

39. Polach, H.A. and J.J. Stipp. "Improved Synthesis Techniques for Methane and Benzene Radiocarbon Dating." International Journal of Applied Radiation and Isotopes 18 (1967): 359-64.

The Australian National University Radiocarbon Dating Laboratory system utilizing both methane gas proportional and benzene liquid scintillation counting is described. This combination allows for independent cross-checks of radiocarbon dates obtained and has the further advantage of requiring only a small capital investment to expand the capacity. Methods of preparation of CO_2, Benzene and methane are described in detail.

40. Pringle, R.W., W. Turchinetz and B.L. Funt. "Liquid Scintillation Techniques for Radiocarbon Dating." Review of Scientific Instruments 26 (1955): 859-65.

A detailed report of a study begun in 1952 to determine the applicability of liquid scintillation methods for radiocarbon measurements. Two methods tested are described in detail and the usefulness of the two are compared.

41. Srdoc, D. and A. Sliepcevic. "Carbon Dioxide Proportional Counters: Effects of Gaseous Impurities and Gas Purification Methods." International Journal of Applied Radiation and Isotopes 14 (1963): 481-88.

A series of experiments are described in which the effects of contamination of CO_2 on counting properties of CO_2-filled counters are tested. Successful use of a method of purification using a vacuum technique is presented; it is concluded that accuracy in low-level counting and in particular, radiocarbon dating can be improved through use of this method.

42. Tamers, M.A. "Chemical Yield Optimization of the Benzene Synthesis for Radiocarbon Dating." International Journal of Applied Radiation and Isotopes 26 (1975): 676-82.

A benzene synthesis vacuum line for radiocarbon dating is described and studies to optimize conditions are presented. The total procedure has been shortened for most archaeological samples by substitution of a preliminary carbonization step for the usual combustion.

43. Tamers, M.A. "Routine C-14 Dating Using Liquid Scintillation Techniques." In Proceedings of the Sixth International Conference: Radiocarbon and Tritium Dating, Pullman, Washington, 1965, pp. 53-68. U.S. Atomic Energy Commission, Division of Technical Information, 1966.

This paper provides a detailed description of the liquid scintillation techniques as developed and used by the Radiocarbon Laboratory of the University of Texas and the Instituto Venezolano de Investigaciones Cientificas. A

list and discussion of the advantages of this technique over other methods is included.

44. Switsur, V.R. "Combustion Bombs for Radiocarbon Dating." In Proceedings of the Eighth International Radiocarbon Dating Conference, pp. B11-B23. Wellington: New Zealand Royal Society, 1972.

This paper consists of a discussion of the several advantages of bomb combustion compared to the conventional oxidation in a heated quartz tube. This method may be used for all normal types of samples, and new developments are noted which bring difficult samples such as lake-mud and soils of very low carbon content within the scope of the method.

IV. LIMITATIONS AND SOURCES OF ERRORS

45. Anderson, E.C. and W.F. Libby. "World-wide Distribution of Natural Radiocarbon." Physical Review 81 (1951): 64-69.

Report of an early attempt to compare the radiocarbon content of samples of biological materials from locations widely scattered over the earth. The results indicated no evidence of latitudinal variation in radiocarbon content; this supports the expected short relative turnover time for radiocarbon in the biosphere.

46. Barbetti, M. "Geomagnetic Field Behavior Between 25,000 and 35,000 Years B.P. and Its Effect on Atmospheric Radiocarbon Concentration: A Current Report." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, pp. A104-1113. Wellington: Royal Society of New Zealand, 1972.

Some preliminary data on the variation in geomagnetic field intensity during the period from 25,000 to 30,000 years B.P. are presented. These data suggest there may have been much larger variations in the atmospheric concentration of radiocarbon during this period.

47. Baxter, M.S. and A. Walton. "Fluctuations of Atmospheric Carbon-14 Concentrations During the Past Century." Proceedings of the Royal Society, Series A, 321 (1971): 105-27.

A detailed report of studies done at the University of Glasgow to determine variations in atmospheric C-14 concentrations during the past century. Materials analyzed in the studies included wines, spirits and plant seeds, chosen for their availability, purity and knowledge of exact time and place of growth. Results indicate short-term fluctuations in C-14 concentrations negatively correlated with solar activity. It is proposed that the fluctuations are the result of solar-sensitive mixing of stratospheric and tropospheric air masses through variations of radiation received over each solar cycle. These variations may introduce further uncertainty into the dating of "young" materials.

48. Bray, J.R. "Atmospheric Carbon-14 Content During the Past Three Millennia in Relation to Temperature and Solar Activity." Nature 209 (1966):1065.

Recent summaries of temperature, glacial activity and solar activity are used as the basis of an attempt to explain discrepancies in interpretations of carbon-14 - climate relationships. Carbon-14 in relation to climate A.D. 1200-1860, climate 1200 B.C. to A.D. 1200, temperature, and solar activity are discussed.

49. Bray, J.R. "Variation in Atmospheric Carbon-14 Activity Relative to Sunspot-Auroral Solar Index." Science 156 (1967): 640-42.

The author presents an analysis of the relationship between solar activity and atmospheric radiocarbon activity based on a combined sunspot and auroral index of solar activity and an augmented set of radiocarbon activity data. The result is a consistent pattern of alternating increases and decreases in C-14 activity with alternately lower and higher solar activity periods.

50. Bucha, V. "Influences of the Earth's Magnetic Field on Radiocarbon Dating." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 501-12. New York: Wiley-Interscience, 1970.

Archaeomagnetic investigations of the changes in the earth's magnetic intensity in the past 10,000 years are reported and compared graphically to deviations in the carbon-14 content. Similarity in the curves indicated that fluctuations in radiocarbon production correlate inversely with changes in the earth's magnetic intensity.

51. Burleigh, R. and A. Hewson. "Evidence for Short Term Atmospheric ^{14}C Variations About 4000 Yr. B.P." Nature 262 (1976): 128-30.

A discussion of the uncertainty concerning short-term (10-20 years) variations in the natural atmospheric level of C-14 is followed by a report of the results of radiocarbon measurements on Red Deer antlers from Neolithic flint mines at Grime's Graves, Norfolk. These results contradict archaeological evidence; it is therefore proposed that the measured ages reflect an atmospheric C-14 variation of at least 2% in a period of 10 years or less.

52. Damon, P.E., A. Long and D.C. Grey. "Fluctuations of Atmospheric C-14 During the Last Six Millennia." Journal of Geophysical Research 71 (1966): 1055-63.

This article describes work done at the University of Arizona Geochronoloty Laboratory in estimating fluctuations of the initial C-14 content of the atmosphere by measurements on dendrochronologically dated woods. A lengthy description of the methods of preparing the wood samples is provided and graphs depicting the variations of C-14 are also given.

* 53. Dergachev, V.A. and G.E. Kocharov. "Radiocarbon Content in the Earth's Atmosphere and Cosmic Ray Time Variations." Conference Paper, International Cosmic Ray Conference, 1973. (NTIS, Springfield, Va.)

The theoretical and experimental principles of a new approach to the study of cosmic ray time variations for

the last tens of thousands of years are discussed. Consideration is successively given to the problems of correlation between the radiocarbon concentration in the terrestial atmosphere and time variation and inversion of geomagnetic field; flares of supernovas; the cyclic and burst activity of the sun. (Chemical Abstracts)

54. Farmer, J.C. and M.S. Baxter. "Short-term Trends in Natural Radiocarbon." In Proceedings of the Eighth International Radiocarbon Dating Conference, pp. A58-A71. Wellington: Royal Society of New Zealand, 1972.

A discussion of studies in which radiocarbon assay of single tree-rings for the period 1829-65 indicates a significant correlation of atmospheric C-14 levels in the northern hemisphere with sunspot number over the 11-year solar cycle. That such a correlation is not apparent in the southern hemisphere from twentieth century data suggests that the solar-terrestial relationship, involving variations in C-14 production and atmospheric exchange, may vary with latitude and time.

55. Libby, L.M. "Globally Stored Organic Carbon and Radiocarbon Dates." Journal of Geophysical Research 78 (1973): 7667-70.

The author discusses the effect on radiocarbon dates of variations in the amount of carbon stored globally as organic material that originated in the biosphere. New measurements of global evolution of CO_2 are used to explain short-term variations in the amount of radiocarbon in tree rings.

56. Libby, W.F. "Radiocarbon and Paleomagnetism." In Proceedings of the Sixth International Conference: Radiocarbon and Tritium Dating, Pullman, Washington, 1965, pp. 348-56. U.S. Atomic Energy Commission, Division of Technical Information, 1966.

A discussion of the relationship between the variation of the earth's magnetic field and the radiocarbon content of living matter. It is concluded that, due to this relationship, radiocarbon dates can be used as a measure for study of paleomagnetism.

57. Neustupný, E. "The Accuracy of Radiocarbon Dating." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 23-34. New York: Wiley-Interscience, 1970.

A review of the sources of error in radiocarbon dating is provided. Discussed are errors of measurement, error in the laboratory, contamination of samples, true age of the materials involved and error from variations in the concentration of radiocarbon.

58. Nydal, R. "On the Transfer of Radiocarbon in Nature." In Radioactive Dating and Methods of Low-Level Counting, pp. 119-28. Vienna: International Atomic Energy Agency, 1967.

This paper consists of a detailed description of tests to determine an exchange calculation for the rate of radiocarbon transfer among the various natural reservoirs. Artificial radiocarbon from nuclear tests performed in 1961 and 1962 was used as a tracer in the tests described.

59. Ralph, E.K. and H.N. Michael. "Problems of the Radiocarbon Calendar." Archaeometry 10 (1967): 3-11.

The authors discuss the problems related to fluctuations in the amount of C-14 in the atmosphere and the causes thereof. Correlations of C-14 dates and known ages of materials tested are presented graphically and discussed in the text.

60. Schell, W.R., A.W. Fairhall and G.D. Harp. "Measurements of Carbon-14 in Known Age Samples and Their Geophysical Implications." In Proceedings of the Sixth International Conference: Radiocarbon and Tritium Dating, Pullman, Washington, 1965, pp. 396-414. U.S. Atomic Energy Commission, Division of Technical Information, 1966.

This paper describes a program undertaken to achieve a better understanding of the present limitations of the carbon-14 dating method. The program involved extensive analysis of samples of known age in order to confirm or negate some of the effects attributable to cosmic ray variations, climate and other factors. The data compiled in these analyses indicate a slow decrease in the C-14 concentration in the atmosphere. The possibility of using C-14 in research on past climatic conditions is suggested.

61. Stuiver, M. "Long-term C^{14} Variations." In Olsson, I.U., Radio-Carbon Variations and Absolute Chronology, pp. 197-213. New York: Wiley-Interscience, 1970.

A discussion of lake-sedimentation rates and lake-varve chronology as means of providing information on long-term atmospheric C-14 changes. The advantages of this method over tree-ring research is the longer time span available for study.

62. Stuiver, M. "Origin and Extent of Atmospheric ^{14}C Variations During the Past 10,000 Years." In Radioactive Dating and Methods of Low-Level Counting, pp. 27-40. Vienna: International Atomic Energy Agency, 1967.

This study reports the detailed C-14 analysis of sediments flooring three lakes: Rogers Lake, Connecticut; Lake Victoria in Africa and Lake Yueh Tan in Formosa. The lakes were chosen from widely different latitudes

to avoid variations induced by local climatic changes. This study affirms the change in time scale observed in C-14 ages of tree rings and Egyptian samples of known ages around 2500 B.P. Other conclusions from the study are discussed.

63. Suess, H.E. "Secular Variations of the Cosmic-Ray-Produced Carbon-14 in the Atmosphere and Their Interpretations." Journal of Geophysical Research 70 (1965): 5937-52.

This paper presents the results of 130 radiocarbon measurements of wood of known time of growth, made in 1963 and 1964 by the La Jolla Laboratory. The results confirm that the specific C-14 activity of carbon dioxide in the atmosphere shows small changes with time. It is concluded that changes in C-14 activity are caused primarily by changes in the production rate of C-14 resulting from variations of the cosmic-ray flux by the sun.

64. Walton, A, M. Ergin and D.D. Harkness. "Carbon-14 Concentrations in the Atmosphere and Carbon Dioxide Exchange Rates." Journal of Geophysical Research 75 (1970): 3089-98.

A report of investigations made during a three-year period of C-14 variations in the stratosphere and in the troposphere, in prder to provide data for a further appraisal of values of CO_2 transport parameters. Due to the cessation of large-scale atmospheric nuclear tests in 1962, the C-14 concentrations showed a steady decline from 1963 in the Northern hemisphere.

V. CALIBRATION OF THE RADIOCARBON CHRONOLOGY

65. Berger, R. "Ancient Egyptian Radiocarbon Chronology." Philosophical Transactions of the Royal Society, Series A, 269 (1970): 23-36.

A description of results from carbon-14 testing of historically well-dated Egyptian samples from the time period of the I to XXX dynasties. The article includes detailed descriptions and references to the actual materials tested. The radiocarbon and historic chronologies are not significantly different to the time of the XII dynasty. The conversion of radiocarbon dates to calibrated dates closer to the presently accepted historical chronology using bristlecone pine correlation is discussed.

66. Berger, R. "Tree-Ring Calibration of Radiocarbon Dates." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, pp. A97-A103. Wellington: Royal Society of New Zealand, 1972.

Experiments conducted over the past three years to check the diffusion of tree-sap across the tree-rings in mature bristlecone pines with the aid of elevated levels of radiocarbon are described. All observations made confirm the isotopic integrity of carbon molecules in high-polymer wood substances. Consequently, individual trees can be used to assess the climatic, geomagnetic and radiation environment of any respective year.

67. Burleigh, R. "Calibration of C-14 Dates: Some Remaining Uncertainties and Limitations." In Watkins, T., Radiocarbon, Calibration and Prehistory, pp. 5-8. Edinburgh: The University Press, 1975.

A brief review is presented of the interpretation of radiocarbon dates in terms of calendar years. An outline is given of the factors which make such correlations necessary and of the work that has so far been done to make them possible. The calibration of the C-14 time scale very largely depends at present on the bristlecone pine chronology, but it is clear that many difficulties still remain. These are discussed.

68. Cain, W.F. and H.E. Suess. "Carbon-14 in Tree Rings." Journal of Geophysical Research 81 (1976): 3688-94.

Two types of experimentation used to determine how reliably the carbon-14 content of tree rings reflects that of atmospheric carbon dioxide are described.

69. Clark, R.M. and C. Renfrew. "A Statistical Approach to the Calibration of Floating Tree-Ring Chronologies Using Radiocarbon Dates." Archaeometry 14 (1972): 5-19.

Development of a statistical approach assuming linear regression is described. The result is used to position

the floating tree-ring chronologies at Swiss neolithic sites. This method gives objective estimated dates with estimates of error related to the inherent inaccuracies of the radiocarbon dates.

70. Clark, R.M. and C. Renfrew. "Tree-ring Calibration of Radiocarbon Dates and the Chronology of Ancient Egypt." Nature 243 (1973): 266-70.

A statistical investigation is used to compare the functions relating Egyptian historical dates to the corresponding radiocarbon dates; and the bristlecone pine dates to the corresponding radiocarbon dates. It is concluded that the calibrated radiocarbon dates for Egypt do not differ significantly from the historic dates, although errors associated with these make a precise comparison impossible. The general validity of both the radiocarbon and the Egyptian historical chronology are supported by the analysis, but further accurate work on the Egyptian material is still required to reduce the level of error.

71. Damon, P.E., A. Long and E.I. Wallick. "Dendrochronologic Calibration of the ^{14}C Time Scale." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, p. A28-A43. Wellington: Royal Society of New Zealand, 1972.

An accurate state-of-the-art conversion table is presented based on newly available data. Sufficient data are now available to provide for conversion from radiocarbon to tree years for the last 7355 years B.P.

72. Damon, P.E. and others. "Dendrochronologic Calibration of the Radiocarbon Time Scale." American Antiquity 39 (1974): 350-66.

This paper provides a conversion table for single radiocarbon dates. The table is based on data from five laboratories which determined radiocarbon ages of wood supplied primarily from the University of Arizona Laboratory of Tree-ring Research.

73. Edwards, I.E.S. "Absolute Dating From Egyptian Records and Comparison with Carbon-14 Dating." Philosophical Transactions of the Royal Society, Series A, 269 (1970): 11-18.

A discussion of the Egyptian calendar and other sources upon which the historical chronology is based. Comparison with the carbon-14 measurements are given in tabular form.

74. Ferguson, C.W. "Dendrochronology of Bristlecone Pine, Pinus Aristata; Establishment of a 7484-year Chronology in the White Mountains of Eastern-central California." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 237-61. New York: Wiley-Interscience, 1970.

This paper summarizes developments in dendrochronological

research, including the extension of the former 7104-year tree ring chronology by an additional 380 years. Various aspects of chronology building and the use of dated bristlecone pine in radiocarbon studies are discussed.

75. Ferguson, C.W. "Bristlecone Pine: Science and Esthetics." Science 159 (1968): 839-46.

A survey of the development and use of a 7100-year tree-ring chronology for bristlecone pine. The relation of this chronology to radiocarbon datine and, in particular, the studies made in cooperation with radiocarbon labs at the universities of Arizona, California (San Diego) and Pennsylvania are discussed.

76. Long, A. and B. Rippeteau. "Testing Contemporaneity and Averaging Radiocarbon Dates." American Antiquity 39 (1974): 205-15.

Techniques for interpreting arrays of radiocarbon dates are given. These include weighted averaging, statistical rejection of data and the evaluation of contemporaneity. The need for averaging and a discussion of when averaging is appropriate are also included.

77. McKerrell, H. "Correction Procedures for C-14 Dates." In Watkins, T. Radiocarbon, Calibration and Prehistory, pp. 47-100. Edinburgh: The University Press, 1975.

This paper brings together and compares with an independently based procedure, the various correction curves and tables published up to Spring, 1974. Correction results from reliable, historically dated Egyptian, Helladic and Minoan test samples are also presented in detail.

78. McKerrell, H. "Conversion Tables." In Watkins, T. Radiocarbon, Calibration and Prehistory, pp. 110-27. Edinburgh: The University Press, 1975.

Tables are presented for the conversion of standard C-14 dates to calendar years. The major part of the data converts C-14 dates to tree-ring dates; additional data are given, based on the Egyptian historical curve.

79. Michael, H.N. and E.K. Ralph. "Discussion of Radiocarbon Dates Obtained from Precisely Dated Sequoia and Bristlecone Pine Samples." In Rafter, T.A., Proceedings of the Eighth International Radiocarbon Dating Conference, pp. A11-A27. Wellington: Royal Society of New Zealand, 1972.

A set of correction factors for radiocarbon dates of archaeological specimens is presented in tabular form. The methods by which the correction factors were derived are discussed.

80. Ottaway, J.H. and B. Ottaway. "Irregularities in the Dendrochronological Calibration Curve." In Watkins, T. Radiocarbon, Calibration and Prehistory, pp. 28-38. Edinburgh: The University Press, 1975.

Discussion of the possibility of short-term deviations from a linear or smooth curve relating conventional C-14 dates to dendrochronological measurement. The possibility of the effect of short term changes in the earth's atmosphere and in the oceans, and their temperature, is considered.

81. Renfrew, C. and R.M. Clark. "Problems of the Radiocarbon Calendar and Its Calibration." Archaeometry 16 (1974): 5-18.

A review of the basic principles of construction of a calibration curve, with discussion of the limitations of the method. It is concluded that the general principles are sound, but more critical handling of measurement data is needed, as well as improvement of the data itself.

82. Renfrew, C. "The Tree-ring Calibration of Radiocarbon: an Archaeological Evaluation," Proceedings of the Prehistoric Society 36 (1970): 280-311.

The author discusses the impact of radiocarbon dating on existing historical chronologies and the effects the introduction of a dendrochronologically calibrated radiocarbon chronology have had. The three major areas of disagreement between the conventional and the calibrated chronologies are discussed.

83. Säve-Söderbergh, T. and I.U. Olsson. "C^{14} Dating and Egyptian Chronology." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 35-53. New York: Wiley-Interscience, 1970.

A detailed description of the Egyptian historical chronology and the C-14 dates which have been obtained for Egyptian materials are presented. The fact that there has been no attempt to check the C-14 dates systematically is mentioned as a step which should be done.

84. Suess, H.E. "Bristlecone Pine Calibration of the Radiocarbon Time-Scale 5200 B.C. to the Present." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 303-11. New York: Wiley-Interscience, 1970.

This paper describes the measurements done by the La Jolla Radiocarbon Laboratory on dated bristlecone pine wood obtained from the Laboratory of Tree-Ring Research at the University of Arizona. Calibration curves derived from the measurements are included, with a detailed explanation of the meaning of radiocarbon dates and the use of the calibration curve.

85. Switsur, V.R. "The Radiocarbon Calendar Recalibrated." Antiquity 47 (1973): 131-37.

An examination of and comparison of two attempts at calibrating the radiocarbon time scale. The attempts were made by Drs. Michael and Ralph of the University of Pennsylvania and Drs. Damon, Long and Wallick of the University of Arizona. Because of the discrepancy between the results of the two studies, the 8th International Conference on Radiocarbon Dating could not recommend the exclusive use of either one. Dr. Switsur of the Radiocarbon Dating Research Laboratory examines how the two correlations were obtained and by how much they disagree.

86. Tauber, H. "Scandinavian Varve Chronology and C^{14} Dating." In Olsson, I.U., Radiocarbon Variations and Absolute Chronology, pp. 170-196. New York: Wiley-Interscience, 1970.

A general discussion of the Swedish varve chronology, followed by a comparison of the revised varve chronology with C-14 dates over the period 3000 to 12,500 BP. Implications of the deviations between varve years and C-14 years are presented.

87. Waterbolk, H.T. "Working With Radiocarbon Dates." Proceedings of the Prehistoric Society 37 (1971): 15-33.

A number of propositions offered to improve the utilization of C-14 dates in archaeology. Discussion of the dendrochronologically calibrated time-scale is included. Due to the totally different nature of data on which they are based, it is recommended that historical and C-14 chronologies not be mixed.

88. Wendland, W.M. and D.L. Donley. "Radiocarbon-Calendar Age Relationship." Earth and Planetary Science Letters 11 (1971): 135-9.

Report of a study conducted at the Center for Climatic Research at the University of Wisconsin in which 500 radiocarbon dates from eight laboratories were analyzed by multiple regression and 250-year means. The calendar-radiocarbon age relationships for individual labs are presented.

*Indicates articles which were unavailable for my examination